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Professor William T. Trotter

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The goal of the AFOSR DURIP Grant was to assist the Mathematics Program at ASU in acquiring equipment for an Advanced Graphics Computing Facility. Our computers have made possible a breakthrough in unravelling the topology and geometry of some critical phenomena in turbulence, which closely blend chaotic dynamics with classical moderate turbulence. Interactive graphics visualization enabled us to describe the qualitative global nature of numerical solutions and interpret key features from the huge volume of numerical output.

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AFOSR DURIP GRANT
to Mathematics Department, Arizona State University

FINAL REPORT

l The goal of the AFOSR DURIP Grant was to assist the Mathematics Program at ASU in acquiring equipment for an Advanced Graphics Computing Facility. The cornerstone of our Facility is three mini-supercomputers with both vector capabilities and highly interactive graphics; these are Titan machines manufactured by Ardent/Stardent Computer Co:

— one Titan with 4 processors, 62 MB of RAM memory, 1.08 gigabyte of disk space.

— one Titan with a single processor, 32 MB of RAM memory, 720 megabytes of disk space.

— a third Titan with a single processor, otherwise similar to the second machine.

The Advanced Computing Facility is further enhanced by a desktop Data General AVIION computer (18 mips performance) and a laser printer. The whole facility is ethernetted and accessible via BITNET/INTERNET. The cost of the whole facility was about 270K, including discount; this corresponds to substantial enhancement of the DURIP funds.

Our computers have made possible a breakthrough in unravelling the topology and geometry of some critical phenomena in turbulence, which closely blend chaotic dynamics with classical moderate turbulence. Interactive graphics visualization enabled us to describe the qualitative global nature of numerical solutions and interpret key features from the huge volume of numerical output. / This is described below in the synopsis of research projects spearheaded by our Titans:

1) *Large Scale Vortices and Homoclinic Chaos in Periodic Navier-Stokes Flows*

Turbulence is basically a spatially extended system which develops complex spatio-temporal behavior. The dynamical systems approach developed in the last two decades has

proved useful in providing new insight into the problem. In addition to the characterization of the deterministic nature of chaotic motions in turbulent flows, the study of the transition to turbulence in spatially extended systems has provided much information on the dynamical mechanisms of the generation of stochastic and coherent structures.

Our present work demonstrates phenomena of spatially extended chaos and spatio-temporal intermittency in some flows governed by the Navier-Stokes equations. In addition, we develop a dynamical system description of the temporal intermittent bursting events in terms of homoclinic cycles, which have been conjectured for real flow systems by many authors, especially in connection with boundary layer turbulence.

We report here a study of a concrete Navier-Stokes flow system, the two-dimensional Kolmogorov flow, in which an enhanced transport phenomenon occurs intermittently related to symmetry-breaking heteroclinic orbits. This is the two-dimensional flow of a viscous liquid induced by a unidirectional force periodic in one of the coordinates:

$$\frac{\partial u}{\partial t} + u \cdot \nabla u + \nabla p = \frac{1}{Re}\Delta u + F, \tag{1}$$

$$\text{div } u = 0, \quad 0 \le x, y \le L, \quad F = \gamma(\cos k_c y, 0),$$

together with periodic boundary conditions. For this flow, the generalized system of small-scale eddies turns out to be unstable to long-wave instabilities. The Kolmogorov flow is closely related to special A-B-C (Arnold-Beltrami-Childress) 3D flows.

For the Kolmogorov Flow, we evidence dynamical regimes for Re up to $O(100)$ characterized by sparsely distributed bursts in time. The most striking feature of this transition is that the bursts generate substantial spatial disorder and drive developed turbulence. The bursts generate a high degree of stochasticity and a large amount of enstrophy, while the flow remains fairly organized in the mean time outside of the bursts, with large scale vortices dominating the dynamics. We show that heteroclinic orbits connect some equivariant hyperbolic states under symmetry groups of the equations. The homoclinic cycle is the sum of individual heteroclinic connections. Such equivariant states are associated

to large scale vortices. Indeed, the intermittent chaotic (turbulent) behavior of the Kolmogorov flow is deeply connected with its groups of symmetries and related symmetry breakings.

2) *Spatio-Temporal Chaos for One-Dimensional Partial Differential Equations (PDEs)*

This covers in-depth investigation of the cascades of bifurcations for the Kuramoto-Sivashinsky and Kolmogorov-Spiegel-Sivashinsky PDEs modeling spatio-temporal chaos. Other PDEs will be investigated within this context.

3) *Control of Low Dimensional Dynamical Systems*

This project centers on controlling periodic and steady state solutions of dynamical systems with polynomial nonlinearities away from chaos. Interactive graphics visualization of the high dimensional phase space plays a key role.

4) *Interface Stability Problems for the Growth of Crystals in a Zero-Gravity Environment*

Among the future missions of the Space Shuttle Program is the growth of very large crystals for the next generation of semiconductors through a continuous meltdown process. Liquid/surface instability problems arise in a nontrivial fashion with Benard-Marangoni effects. Thresholds of instabilities are computed with the Titan machines. This project is joint with the Aerospace Engineering Department at ASU.